The Haptic Bracelets: learning multi-limb rhythm skills from haptic stimuli while reading

Book Section

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Abstract

The Haptic Bracelets are a system designed to help people learn multi-limbed rhythms (which involve multiple simultaneous rhythmic patterns) while they carry out other tasks. The Haptic Bracelets consist of vibrotactiles attached to each wrist and ankle, together with a computer system to control them. In this chapter, we report on an early empirical test of the capabilities of this system, and consider design implications. In the pre-test phase, participants were asked to play a series of multi-limb rhythms on a drum kit, guided by audio recordings. Participants' performances in this phase provided a base reference for later comparisons. During the following passive learning phase, away from the drum kit, just two rhythms from the set were silently 'played' to each subject via vibrotactiles attached to wrists and ankles, while participants carried out a 30-minute reading comprehension test. Different pairs of rhythms were chosen for different subjects to control for effects of rhythm complexity. In each case, the two rhythms were looped and alternated every few minutes. In the final phase, subjects were asked to play again at the drum kit the complete set of rhythms from the pre-test, including, of course, the two rhythms to which they had been passively exposed. Pending analysis of quantitative data focusing on accuracy, timing, number of attempts and number of errors, in this chapter we present preliminary findings based on participants' subjective evaluations. Most participants thought that the technology helped them to understand rhythms and to play rhythms better, and preferred haptic to audio to find out which limb to play when. Most participants indicated that they would prefer using a combination of haptics and audio for learning rhythms to either modality on its own. Replies to open questions were analysed to identify design issues, and implications for design improvements were considered.

1 Introduction

The acquisition and refinement of rhythm skills is generally vital for musicians. One particularly demanding aspect of rhythmic skills concerns multi-limb rhythms, i.e., multi-stream rhythms that require the coordinated use of hands and feet. The mastery of such rhythms is essential for drummers, but can also be highly beneficial to other musicians, for example piano and keyboard players (Gutcheon 1978). Dalcroze (Juntunen 2004) and others further suggest that the physical enaction of rhythms is essential even for the development of non-performance rhythm skills, such as exercised in composition and analysis. Crucially, physical enaction of many basic building blocks of rhythm, such as standard polyrhythms, is difficult without the coordinated use of multiple limbs. More broadly, it has been claimed that these skills may be able to contribute to general well-being, for example in improving mobility (Brown 2002) and alertness, and helping to prevent falls for older people (Juntunen 2004; Kressig et al. 2005). The development of skills of this nature may also be relevant in rehabilitation, for example from strokes or injury (Huang et al. 2010).

In recent experiments, we demonstrated that the use of haptics (vibrotactile devices) can support the learning of multi-limb rhythms of various kinds (Holland et al. 2010). These experiments featured a system called the Haptic Drum Kit. This system consists of: haptic devices (standard vibrotactiles in the original version, and more specialised tactors in the revised version) attached to the wrists and ankles; a computer system that feeds signals to the haptic devices; and a midi drum kit, which is played by the person while wearing the haptic devices, and which allows accurate data collection. These experiments showed that:

a) haptic guidance alone can be used with similar success compared to audio guidance to support the acquisition of multi-limb rhythms,
b) the combination of the two kinds of guidance is preferred to either kind alone, and
c) haptic guidance has advantages for certain tasks (e.g. knowing which event goes with each limb) but disadvantages for other tasks (energetic body movement can mask the haptic signals).

These experiments also suggested a wide range of other applications. The current experiment aims to examine whether *passive* learning of multi-limb rhythms can occur when haptic rhythmic stimuli are applied away from a drum kit, or any other instrument, when the wearer is performing non-musical tasks, such as reading comprehension. That is to say, we are investigating the acquisition of skills enabled by experiencing haptic stimuli while distracted by another activity.

2 Background

In the case of at least some musical skills, learning via haptic systems is known to be possible. For example, Grindlay (2008) created a mechanical installation that employs haptic guidance by automatically moving a single drumstick that the learner was holding, and showed that this supported learning of rhythms which can be played with one hand. This contrasts in significant respects with the focus of the present study, in that we are interested specifically in multi-limb skills, for reasons outlined earlier, and we are particularly keen to explore the possibilities of passive learning with hands and feet free for other tasks.

Passive learning of at least one related musical skill has been demonstrated. Huang et al. (2008) built a system using a wireless haptic glove with vibrotactile effectors for each finger and demonstrated that users wearing the glove improved their performance at playing simple piano tunes after passive exposure to combined audio and haptic playback, while focused on another task. Participants in their study considered the haptic glove as uncomfortable to wear, however. Furthermore, the results of a later study indicated poor performance related to rhythm (Huang et al. 2010). The focus on fingers of one hand rather than multiple limbs also makes their system unsuitable for our purposes.

More details on the above research and other related work is discussed in section 5.

3 The Haptic Bracelets

The vision behind the present study is of a portable haptic music player, i.e., a "Haptic iPod"[1], which can be worn all day while the wearer performs other tasks. Such an envisaged system would play music, like any other music player, while also transmitting associated rhythms to all four limbs as haptic pulses delivered via lightweight, wireless comfortable bracelets worn on wrist and ankles.

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[1] In earlier work, we referred to a prototype of the family of systems we have designed and built, as the "Haptic iPod". We have now changed the name to the Haptic Bracelets, to avoid any confusion with products of Apple Inc. The Haptic Bracelets have numerous non-musical applications, for example in three-dimensional navigation, fitness, sports and rehabilitation. When it helps to emphasise the specific application to learning multi-limb rhythms, we sometimes use the alternative name "Rhythm Bracelets". The conception, overall design and theory of the Haptic Bracelets are due to Holland. The implementation and design of the current experiment is due to Bouwer. The design and implementation of the static design featured in this chapter is due to Dalgleish.

For practical reasons, the version of the Haptic Bracelets chosen for this experiment is wired and stationary, as opposed to one of our prototype mobile versions. This conservative choice reflected the greater power and reliability of the stationary version at the time of the study. The version used here is essentially a modified version of the Haptic Drum Kit (Holland et al. 2010) without the drums.

The Haptic Bracelets as used in the current experiment employs four 'tactor' vibrotactile devices as the haptic transducers (see Figure 1). These are secured to limbs, as needed, using elastic velcro bands. The tactors are driven by multichannel audio signals controlled from a laptop via a firewire audio interface, amplified by two Behringer high-powered headphone amplifiers.

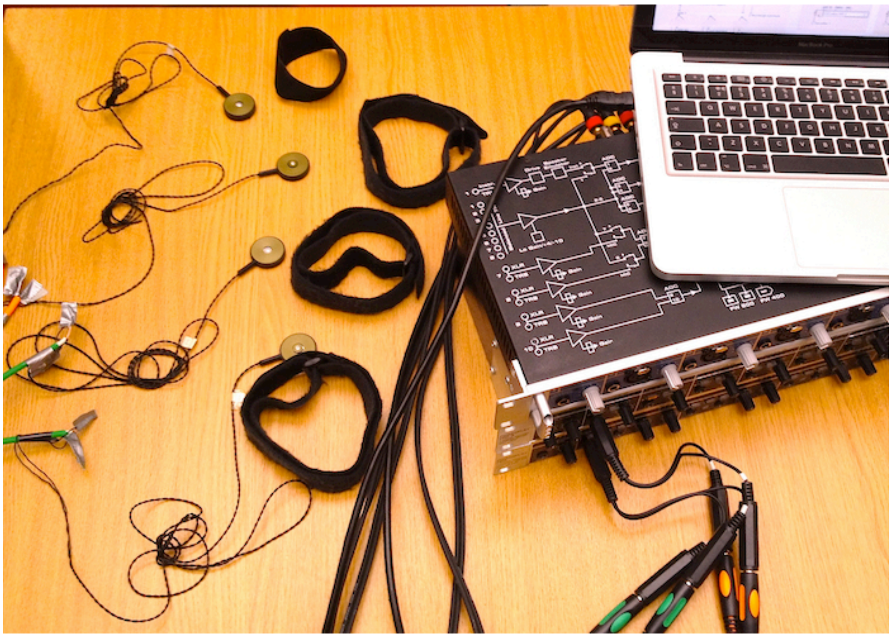

Fig. 1 The static lab-bench version of the Haptic Bracelets, used for passively learning multi-limb rhythms. Four tactors and straps are shown.

The theory behind the Haptic Bracelets draws on three principal areas: sensory motor contingency theory (O'Regan and Noe 2001), human entrainment theory (Clayton, Sager and Will 2004), and Dalcroze Eurhythmics (Juntunen 2004). For a detailed discussion, see Holland et al. (2010).

4 Evaluation of the Haptic Bracelets

To explore the potential of the Haptic Bracelets for passive learning of multi-limb rhythm patterns, an evaluation study was carried out. Preliminary findings based on participants' subjective evaluations are presented below.

Participants
Fifteen people participated in the experiment (eight men and seven women), aged 15-51. Three were experienced drummers (with approximately ten years of experience playing the drums), five had a little drumming experience, and seven had no experience with drumming.

Materials: selection of reference rhythms
To act as reference rhythms, six multi-limb rhythms were drawn from three technical categories. All of these rhythms are challenging for beginners, and some are challenging even for experienced musicians. Each category incorporates multi-limb coordination in a different way. Examples from a fourth category, pure metrical rhythms, were excluded as these are generally the easiest multi-limb patterns to play. The three categories used were as follows:

- linear rudiments, i.e., regular beats rendered figural by the way events are distributed across limbs (i.e., paradiddle);
- cross-rhythms (i.e., systematic polyrhythms);
- syncopated figural rhythms, based on the Cuban clave.

The six specific rhythms were as follows:

- a two handed paradiddle, i.e., RLRRLRLL (see Figure 2);
- a two handed paraparadiddle, i.e., RLRLRRLRLRLL;
- a three against four polyrhythm (see Figure 3);
- a five against four polyrhythm;
- a seven against four polyrhythm;
- a three-two clave combined with a quarter-note beat on the hi-hat, and a tumbao bass pattern (see Figure 4).

Taking representative rhythms from these categories was motivated by evidence from music psychology that the human perception system deals with them in different ways (Arom 1991, Lerdahl and Jackendoff 1983, Smith et al. 1994, Upitis 1987). Choices from these categories were deemed a precaution against over-generalisation of findings based on an overly narrow class of rhythms.

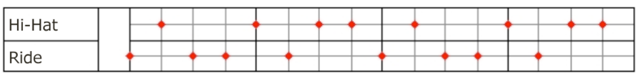

Fig. 2 A paradiddle

Viewed globally, a paradiddle is just a regular uniform beat, consisting of a continuous stream of notes assigned to two different limbs. However, viewed from the perspective of each individual limb, it requires a complex figural pattern to be played, involving single and double strokes and pauses lasting different time intervals. This is more difficult than simply alternating single strokes, where one limb can lead and the other can follow. The paradiddle and paraparadiddle (also called double paradiddle) are very common in instruction for drummers as they form part of the set of basic drumming rudiments. When played on one drum, the alternation of single and double strokes results in subtle variation in emphasis and tone color. As played aurally to subjects in the pre-test (see below), the pattern was distributed over the ride and hi-hat cymbals, to make it easier to discern what the individual limbs should play.

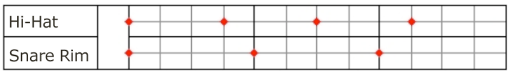

Fig. 3 A two-handed polyrhythm: three against four

Cross-rhythms are systematic polyrhythms that combine two regular pulses played against each other. By nature they are polyphonic and generally played using two limbs. They are built from completely regular layered elements, but they are not hierarchical. That is to say, the periods in slower layers need not coincide with beats in faster layers (because the periods are relatively prime) except at the beginning of complete cycles. Because it is difficult to conceive of multiple meters running at the same time, learning to understand and play such rhythms can be done by counting the lowest common multiple, (e.g., 12 in the case of three against four), and determining which of these beats are played by which limb. The simplest cross-rhythm, two against three, is quite common in many styles of music, and was therefore left out of this study, but more complicated cross-rhythms such as the ones used here are not often found in western musics (although clear examples occur in jazz, fusion, metal, and classical genres). Cross-rhythms are more common in certain Indian, African, and Afro-Cuban music traditions (e.g., see Arom 1991).

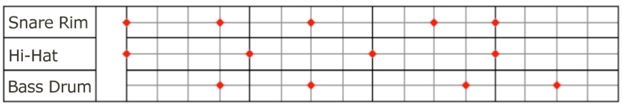

Fig. 4 A Cuban rhythm based on the clave pattern

The Cuban rhythm based on the Son three-two clave (see Figure 4) is a predominantly figural rhythm, where the patterns played by a given limb are irregular due to syncopation (see the top and bottom line, which are played by a hand and a foot, respectively). Furthermore, the combination of syncopated patterns into a polyphonic (multi-limb) orchestration, as in this example, increases the complexity of the rhythm because the combinations of limbs played synchronously differ for different points in time (i.e., some limbs are played simultaneously at certain points in time, while other combinations of limbs cooccur at other points in time). This kind of organization tends to make challenging demands on memorization, analysis, retention and reproduction.

Setup: experimental tasks and methods

(1) The first phase of the experiment was a pre-test phase, in which subjects were asked to play, as best they could, a series of six multi-limb rhythms on a midi drum kit, based on audio playback of each rhythm. These performances served as base reference levels for comparing performances in the post-test phase.

(2) The second phase of the experiment was a passive learning phase, away from the drum kit and in a different room. For this phase, subjects had rhythms silently played back haptically via tactors attached to their wrists and/or ankles while they were engaged in a distraction task. The distraction task was a 30-minute reading comprehension test. During this task, only two rhythms from the set of six in the first phase were 'played' to each subject: different pairs of rhythms were chosen for different subjects, so that clear distinctions could be made in the third phase. Within that constraint, choices were also made to accommodate for different levels of playing experience. In each case, the two different rhythms were repeated and then alternated every few minutes until the end of the task.

(3) The third phase was a post-test phase, in which subjects were asked again to play on the midi drum kit the complete set of rhythms from the pre-test (Figure 5). Clearly, this included the two rhythms to which the subject had been given passive haptic exposure in the second phase. Each subject's performance for all rhythms was compared to the corresponding baseline performances in the pre-test, in terms of accuracy, timing, the number of attempts and the number of errors in their best attempt.

(4) Finally, a questionnaire was administered that asked about subjects' experiences during the experiment, and their attitudes towards the Haptic Bracelets technology.

Fig. 5 Subjects were asked to play the test rhythms without the Haptic Bracelets in pre-test and post-test phases

Clearly, a key outcome will be to determine whether there were measurably greater improvements between pre-test and post test in the case of rhythms for which subjects experienced passive exposure, as compared with the other rhythms. As already noted, these results are still undergoing analysis, so in this chapter we present preliminary results based on participants' subjective evaluations from the questionnaire.

Questionnaire results

In this section, we present participants' responses to the fourteen closed items on the questionnaire in turn. A summary of these responses is given at the end of this section.

Do you like the idea of being able to feel the beat, using haptic technology?
(The possible answers were: 1: I dislike the idea very much, 2: I dislike the idea a little, 3: I feel neutral about the idea, 4: I like the idea a little and 5: I like the idea very much)
The idea of haptically feeling rhythms is clearly appealing, since all participants answered positively to this question. Seven subjects answered "I like the idea a little", and eight subjects answered "I like the idea a lot" (Median = 5, Min = 4, Max = 5). However, we should note that the volunteers coming to participate in this study are likely to be more positive towards the technology than people in general.

How comfortable was it to wear the technology?
(1: very uncomfortable, 2: slightly uncomfortable, 3: neutral, 4: slightly comfortable, 5: very comfortable)
Although the scores were generally more positive than neutral (Median = 4, Min = 1, Max = 4), scores varied among participants, with ten participants scoring 4 (reasonably comfortable), one participant scoring 3 (neutral), two participants scoring 2 (a little uncomfortable), and two participants scoring 1 (very uncomfortable). Seven participants indicated it became slightly more comfortable over the course of the experiment, whereas three participants indicated it became slightly less comfortable over time; the rest indicated it didn't change.

Do you think this technology helped you to play any of the rhythms better?
(1: not at all, 2: a little, 3: a lot)
Eight participants answered 2 (a little) (Median = 2, Min = 1, Max = 3). Three participants reported a score of 1 (not at all), whereas one reported the maximum score of 3 (A lot). Two participants did not answer this question, indicating that they did not feel that they could answer it after experiencing the haptics for only a brief period.

Do you think this technology helped you to understand any of the rhythms?
(1: not at all, 2: a little, 3: a lot)
Seven of the participants scored a 2 (a little) for this question (Median = 2, Min = 1, Max = 3). Five people scored 3 (a lot), which is a more positive reply than for the previous question. Nevertheless, three people scored 1 (not at all).

When you started reading, how much attention did you pay to the pattern of the beat, compared with the reading task?
(1: no attention to the pattern, 2: some attention to the pattern, 3: about evenly split, 4: more than half on the pattern, 5: mostly on the pattern)
When they started reading, the participants reportedly paid slightly less attention to the haptic rhythmic stimuli compared to the reading task (Median = 2, Min = 2, Max = 5). Nine participants scored 2 (Some attention to the pattern), two participants scored 3 (About evenly split), three participants scored 4 (More than half on the pattern), and one scored 5 (Mostly on the pattern). The fact that none of the participants scored 1 (No attention to the pattern) indicates that it is hard to completely ignore the haptic stimuli.

When you had been reading for a while, how much attention did you pay to the pattern of the beat, compared with the reading task?
(1: no attention to the pattern, 2: some attention to the pattern, 3: about evenly split, 4: more than half on the pattern, 5: mostly on the pattern)
After reading for a while, reported attention levels to the haptic stimuli dropped slightly (Median = 2, Min = 1, Max = 4). Two participants now reported a score of 1 (No attention to the pattern).

Which type of information helps most to find out which drum to play when?
(1: audio is much better, 2: audio is slightly better, 3: no preference, 4: haptic is slightly better, 5: haptic is much better)
The participants' scores indicated a slight preference for the haptic information (Median = 4, Min = 1, Max = 5). Five people scored 5 (haptic is much better), whereas two people scored 1 (audio is much better), indicating a wide variety in personal preferences. One person did not answer this question.

Which type of information helps most to find out which limb to play when?
(1: audio is much better, 2: audio is slightly better, 3: no preference, 4: haptic is slightly better, 5: haptic is much better)
For this question, the preference for haptics was even stronger (Median = 5, Min = 2, Max = 5). Eight participants scored 5 (haptic is much better), while only one scored 2 (audio is slightly better). One person did not answer this question.

Which type of information helps most to find out when the pattern repeats?
(1: audio is much better, 2: audio is slightly better, 3: no preference, 4: haptic is slightly better, 5: haptic is much better)
To find out when the pattern repeats, participants only have a slight preference for the haptic information (Median = 3, Min = 1, Max = 5). Three persons indicated a score of 5 (haptic is much better), whereas one indicated a score of 1 (audio is much better). One person did not answer.

Which type of information helps most to understand a rhythm?
(1: audio is much better, 2: audio is slightly better, 3: no preference, 4: haptic is slightly better, 5: haptic is much better)
To understand a rhythm, participants have a slight preference for haptics (Median = 4, Min = 2, Max = 5). Four participants scored a 5 (haptic is much better), against two participants scoring a 2 (audio is slightly better). Two persons left this blank.

Which type of information helps most to play a rhythm?
(1: audio is much better, 2: audio is slightly better, 3: no preference, 4: haptic is slightly better, 5: haptic is much better)
To play a rhythm, there was also a slight preference for haptics (Median = 4, Min = 2, Max = 5). Two people scored a 5 (haptic is much better), against one person scoring a 2 (audio is slightly better). Two people did not answer this question.

How easy was it to play in time with the audio playback?
(1: very difficult, 2: a little difficult, 3: neutral, 4: reasonably easy, 5: very easy)
Most participants found it at least a little difficult to play in time with the audio feedback (Median = 2, Min = 1, Max = 4). Seven people even found it very diffi-

cult (a score of 1), but on the other hand, three participants found it a little easy (a score of 4). Of these last three, one was an experienced drummer, and the two others had some experience with rhythms. The other two experienced drummers scored a 2 (a little difficult), indicating that the materials were not straightforward, not even for experienced drummers.

Would you prefer audio, haptics, or both for learning rhythms?
(1: I prefer audio only, 2: I prefer both audio and haptics, 3: I prefer haptics only)
With a large majority of eleven participants scoring 2 (I prefer both audio and haptics), there is a clear preference for having both audio and haptics (Median = 2, Min = 2, Max = 3). Two participants scored 3 (I prefer haptics only), and nobody indicated a preference for audio only. Two persons did not answer this question. Taken together, this suggests that haptics offer a clear added value, especially when provided together with audio.

Did you enjoy the experiment?
(1: I disliked it very much, 2: I disliked it a little, 3: I feel neutral about it, 4: I liked it a little, 5: I liked it very much)
Overall, the majority of participants enjoyed taking part in the experiment (Median = 5, Min = 2, Max = 5), with eight participants scoring the maximum score of 5 (I liked it very much). However, two participants scored a 2 (I disliked it a little), and one scored a 3 (neutral), indicating that the positive feeling was not universal.

Open Questions
There were six open questions, which are listed below, followed by all replies from participants. A summary of the responses can be found later in the chapter.

Are there things that you liked about using the technology in the training session?

1. “Unfamiliar feeling, tickle. Friendly appearance of the hardware - they beep slightly.” (P1)

2. “It was fun to play the electronic drums.” (P2)

3. “I did not perceive it as ‘training’. My instruction was to read the text. It was nice to feel the rhythm through haptic.” (P3)

4. “Fun to use new technology in novel ways.” (P4)

5. “No. Interesting to find out about another way of learning though.” (P5)

6. “I had to concentrate harder in order to be able to read the text. Of course it was a matter of decision to set the reading task as the priority.” (P7)

7. “Understanding the complexity of different rhythms like learning a language.” (P8)

8. “Clarity of the haptics. ‘seeing’ the repeated foot figure in the son clave. ‘seeing’ how the 4/5 inter plays.” (P9)

9. “I had never played a drum kit like that, so was exciting. (P10)

10. “The buzzers were strong enough to feel.” (P11)

11. “It helped to differentiate between the limbs, whereas using audio feedback it is often hard to separate limb function” (P13)

12. “That it helped me understand the rhythm. (P14)

13. “Being able to flawlessly distinguish between which limb to use. The audio is more confusing.” (P15)

Are there things that you didn't like about using the technology in the training session?

14. “The way the cables were soldered made it feel like one has to be very careful not to move too much. Wireless would be nice, I can imagine.” (P1)

15. “I wish I had a chance to play with haptic on.” (P3)

16. “The comprehension test. Give me some maths.” (P4)

17. “Maybe a bit annoying after some time.” (P7)

18. “Started to get a little irritating after a while due to the repetitive nature.” (P8)

19. “Having to do the reading. Let's have a portable one.” (P9)

20. “No dislike.” (P10)

21. “I was useless!” (P12)

22. “That it didn't allow for me to physically practice much, because I find it difficult to play a polyrhythm; I have to build a physical memory.” (P13)

23. “That the audio made it difficult to differentiate between which drums needed to be played.” (P14)

24. “The wrist/ankle strap/haptics cables are unwieldy - but that can't be helped.” (P15)

Are there things that you like about the haptic playback?

25. “It makes the playing of complex patterns easier to understand.” (P2)

26. “I can feel the rhythm better.” (P3)

27. “Helps to concentrate on individual limbs.” (P4)

28. “Being able to distinguish right and left more easily.” (P5)

29. “I like the technology cause (it) assists you (to) embody the rhythm in a new promising way.” (P7)

30. “Knowing your left from your right.” (P8)

31. “Clarity of timing. Clarity of assignment of limb to time stream.” (P9)

32. “Easier to concentrate on the particular rhythms within a polyrhythm (than audio only).” (P10)

33. “The haptic allows you to think the process through before you actually play. It may reduce the likelihood of learning wrong patterns.” (P13)

34. “That you could easily feel which drums you needed to play when and how quickly it went on to the next beat.” (P14)

35. “The distinction between instruments (limbs).” (P15)

Are there things that you don't like about the haptic playback?

36. “Might be annoying or distracting or boring to use in everyday life. Would rather listen to actual music.” (P5)

37. “(Neutral) repetition gets irritating 'under the skin'” (P8)

38. “Just initially strapping on the legs. Portability.” (P9)

39. “The ankle vibrations felt weak on me and I had to concentrate hard to feel them.” (P10)

40. “On the paradiddle it felt that when the 2 hand buzzers coincided the right one was weaker than the left one.” (P11)

41. “That I didn't hear the audio at the same time.” (P13)

42. “That at times they got a bit annoying.” (P14)

43. “Slightly disorientating when a new rhythm starts playing.” (P15)

Do you have any suggestions to improve the haptics as used in this study?

44. “I would have liked to try the haptics while playing the drums. (P2)

45. “Use it while playing.” (P3)

46. “Sounds are distracting -> Hard to work out where sound is coming from. Need pure vibrations.” (P4)

47. “None that I can think of… end of play brain drain” (P8)

48. “Please go portable and wireless!” (P9)

49. “Have ankle vibrodetectors that have stronger vibrations.” (P10)

50. “Feeling the rhythm whilst listening to the audio would be a lot better to create a more holistic understanding of the polyrhythm and the interaction needed by the limbs.” (P13)

51. “Vary the strength of the vibrations for different limbs.” (P14)

Do you have any other comments?

52. “The laptop mouse pad (used to scroll text and select answers in the reading comprehension test) was hard to use.” (P5)

53. “There was too much to take in - i.e. sequences too long + too many + too complex.” (P5)

54. “Subject's familiarity with playing from score/improvising is probably a key variable.” (P6)

55. “Music is a universal language that can have profound impact on learning and collaboration, building community as part of an oral tradition. The most ancient form of meditation.” (P8)

56. “Quality of haptic 4/5 was more clear than [merely] audio signal.” (P9)

57. “I think participants may need a little time to practice after the haptics without the audio playback on.” (P13)

Summary of findings from the closed responses

The responses to closed items on the questionnaire demonstrated a wide range of attitudes. The system did not meet with universal approval. However, the views of the fifteen participants towards the haptic bracelets as used in the training session were generally positive. The principal findings from this section of the questionnaire can be summarized as follows:

• All users liked the idea of being able to feel the beat using haptic technology.
• 12 of 15 participants thought the technology helped them to *understand* rhythms.
• 9 of 15 participants thought the technology helped them to *play* rhythms better.
• Most participants preferred haptic to audio to find out which *limb* to play when.
• There was a slight preference for haptic to find out which *drum* to play when.
• All participants paid some attention to the haptic stimuli initially while reading.
• After a while, only two participants reported paying no attention at all.
• A clear preference was stated for learning rhythms with *both haptic and audio*.

Summary of issues emerging from the open questions

Several of the responses to open items on the questionnaire suggest design issues, and reflect ways in which the current prototype could be improved. The relevant responses are summarised in four broadly related groups.

The first group of comments identified miscellaneous limitations and annoyances of the system, centered around two aspects: irritation and boredom felt or expected after repeated use (see quotes 17, 18, 36, 37, and 42), and the desire to combine feeling the haptics with listening to audio (quote 41 and 50). Some of these comments may be specific to the current implementation; others may apply to any implementation of the core idea.

One of the most obvious potential benefits of a multi-limb haptic system, the ease of assigning rhythm streams to limbs was noted by several participants (see quote 11, 12, 13, 27, 28, 30, and 31).

The passive haptic stimuli appear to have prompted some participants to reflect insightfully on the rhythms, as evidenced by quotes 8, 27, 28, 32, and 33.

Some comments pointed to options for improved designs, in particular combining the sensation of haptics with playing the drums (quote 15, 44, and 45), as we employed in the Haptic Drum Kit (Holland et al. 2010), using a portable wireless version (quote 48), and more control over the strength of the haptic signals on particular limbs (quote 39 and 40).

For a detailed discussion of the implications of these considerations, see section 6 on design issues and further work.

5 Related Work

The potential of using haptics in learning and training motor skills has been acknowledged in many domains, leading to applications for a diverse range of task types, including learning complex 3D motions (Feygin et al. 2002), learning of force skills (Morris et al. 2007), sensory substitution (Bird et al. 2008), training in snowboarding skills (Spelmezan et al. 2009), and posture for violin players (van der Linden 2011). In most of these systems, the goal is to support learning the desired movement patterns necessary for carrying out the specific task, involving the detection of mistakes and giving haptic signals to correct suboptimal movements. For example, Morris et al. (2007) demonstrated that haptic feedback can enhance the learning of force skills, and Bird et al. (2008) reviewed research in sensory substitution, where one sensory modality is used to facilitate performance in tasks usually guided by another sensory modality. Examples include flight suits that communicate warning information to pilots using puffs of air. Spelmezan et al. (2009) considered a wireless prototype vibrotactile system for real-time snowboard training. This system detected common mistakes during snowboarding and gave students immediate feedback suggesting how to correct their mistakes.

Although some of this work also relates to the movement of multiple limbs, these systems are in general not particularly concerned with timing skills in coordinated multi-limb movement, as in the current study. One finding of relevance to timing skills came from Feygin et al. (2002). In this study, subjects learned to perform a complex motion in three dimensions by being physically guided through the ideal motion. The finding was that although trajectory shape was better learned by visual training, temporal aspects of the task were more effectively learned from haptic guidance.

Within the domain of music, there are numerous systems which incorporate haptic feedback into virtual or physical musical instruments. Examples can be found in O'Modhrain (2000), Collicutt et al. (2009), Sinclair (2007), and Miranda and Wanderley (2006). A project that aims to direct feedback to the players arms, rather than the instrument, was carried out by Van der Linden et al. (2011), who showed that haptic feedback can be used for training in the posture and bowing of violin students.

Work that shares our focus on learning polyphonic rhythms includes the following projects: LapSlapper (Andresen et al. 2010), the Programmable Haptic Rhythm Trainer (Ni 2010), and Polyrhythm Hero (McNulty 2009), LapSlapper (Andresen et al. 2010) allows players to create midi drum sounds by striking their hands on any available surface, such as the player's own body. This is achieved by using piezo microphones attached to gloves, and optionally in a shoe. Outputs from the microphones are converted by Max/MSP into triggers for midi events with midi velocity information. Different microphones may be mapped to different midi instruments. This simple idea, which echoes earlier systems developed by Zimmerman et al. (1987) with just such an aim, and other systems developed by musicians such as Kraftwerk, does not involve technologically mediated haptic feedback, However, drumming varied rhythms on one's own body as method for improving rhythm skills has been long recommended by musicians (Gutcheon, 1978). This was one motivation for both the Haptic Drum kit and the Haptic Bracelets.

The Programmable Haptic Rhythm Trainer (Ni 2010) consists of a demo board with a 4 x 4 keypad and an LCD display. The keypad may be used to enter two rhythms, in a notation reminiscent of a drum machine, as well as other information such as tempo, time signature and number of repeats. The user then rests two fingertips on plastic fittings that cap each of two servomotors. These caps wiggle in time to the two rhythms. The time signature is indicated by a regular clicking sound synchronized with blinks of the LCD. The first beat of each bar is emphasised by a click at a different pitch, as in many electronic metronomes. The imposition of a single time signature seems to make this system less suitable for dealing with polyrhythms, and the encoding of the wiggles appears to encode durations rather than onsets, which may not be ideal for the clear communication of rhythms (though this could be tested empirically). The need to hold fingertips to the motors seems to obviate the possibility of drumming while feeling rhythms.

Polyrhythm Hero (McNulty 2009) is a mobile rhythm training game for the iPhone, with two large buttons labelled 'left' and 'right'. The game challenges users to tap the two rhythms of a polyrhythm simultaneously, one on the left button, and the other on the right button. Any two-voice uniform polyrhythm specifiable by an integer ratio *m:n* can be created as a target rhythm, where *m* and *n* are integers between 1 and 16. The rhythms to be tapped are played to the user as audio using two contrasting percussion timbres. Two optional hints about the rhythm are also available. These are a single periodic pulse from the phone's vibrator at the beat where the two rhythms coincide, and a static graphical illustration showing two lines side by side subdivided into *m* and *n* sections respectively. Based on participants subjective evaluation, the audio and visual clues queues were helpful but the haptic downbeat indicator was more problematic. The author suggests that the nature of the vibration was at fault rather than its conception. From our design experience with various haptic effectors (Holland et al. 2010), we suspect that the haptic pulse produced by the iPhone may have been too blurred to permit the needed temporal resolution for the desired purpose.

Reflecting on these three systems, the Haptic Bracelets share a focus on multi-limbed rhythm skills with Lapslapper, but contrast in that the bracelets provide multi-limbed haptic guidance, and can teach passively as well as actively. The Haptic Bracelets share a common interest in polyrhythm training with Polyrhythm Hero, but differ in several ways: the Haptic Bracelets involve all four limbs; they use haptic stimuli to communicate all rhythmic events, not just common downbeats; the use of haptics in the Haptic Bracelets appears to be better liked and more effective; and the Haptic Bracelets can be used passively as well as actively. Various limitations of the Programmable Haptic Rhythm Trainer as currently reported were noted earlier. To the best of our knowledge, the use of four limb haptic stimuli, especially for teaching rhythm skills, is unique to the Haptic Bracelets and Haptic Drum Kit.

Work that addresses the use of haptics to support (passive) learning of musical tasks involving temporal sequencing includes the work by Grindlay (2008), Lewiston (2008), and Huang et al. (2008; 2010). As already mentioned in section 2, Grindlay (2008) focused on monophonic rhythms where the system physically moved a single hand of a human subject to train in playing monophonic rhythms. Haptics were shown to help significantly to improve performance of playing rhythmic patterns with one hand, and haptic plus audio guidance was found to work best.

Lewiston's (2008) five-key keyboard was designed for a single hand in a fixed position. The keyboard uses computer-controlled electromagnets to guide finger movements during sensorimotor learning of tasks involving sequential key presses, such as typing or playing the piano. Preliminary data suggested that this form of haptic guidance is more effective at teaching musical beginners to perform a new rhythmic sequence, when compared with audio-only learning.

As also noted earlier, Huang et al. (2008) explored the passive learning of rhythmic fingering skills for piano melodies. Later work by Huang et al. (2010) similarly considered a lightweight wireless haptic system with a single fingerless glove containing one vibrotactile per finger. The system was used to teach sequences of finger movements to users haptically, while they performed other tasks. A set of finger movements, if executed correctly and transferred to a musical keyboard, played a monophonic melody. In experiments, target melodies were typically restricted to five pitches, so that no movement of the hand (as opposed to the fingers) was needed. Sample melodies contained rests and notes of different durations. A study demonstrated that passive learning with audio and haptics combined was significantly more effective than audio only. Interestingly, in a second study that compared the amount of time required for subjects to learn to play short, randomly generated passages using passive training versus active training, participants with no piano experience could repeat the passages after passive training alone, while subjects with piano experience often could not.

One item of related research arguably in a category of its own is The Possessed Hand (Tamaki et al. 2011). This system employs a forearm band with 28 electrode pads, which, without any invasive technology, i.e. without penetrating the wearer skin, allows a computer to take fine control of the wearers finger movements for a limited period. This research is perhaps unique for the test subjects' comments, which include "Scary… just scary" and "I felt like my body was hacked". Two beginners were able to play short Kyoto passages making fewer mistakes when their hands were externally controlled using Possessed Hand technology. The designers note that this technology may have future musical applications, but also that issues of reaction rate, accuracy, and muscle fatigue need to be investigated. We would like to stress an important difference between the work by Grindlay (2008) and Tamaki et al. (2011), and our work. They both use a system that physically (and to different degrees involuntarily) controls human movements, while in our work (as well as most other related work) the haptics are only used to communicate signals to guide movement, and the decision to physically act upon these signals remains with the user. This distinction between guidance and involuntary control was blurred in one interesting case described by Huang et al. (2010, p. 798), where one of the 16 participants reported "an involuntary twitch in response to the vibration motors resting just below his second knuckle".

From the above broadly related work, the two projects with most relevant similarities to the present study are the work by Grindlay (2008) and Huang et al. (2008, 2010). We will briefly compare these with the Haptic Bracelets. Grindlay's work shares our focus on the use of haptics for passive learning of drumming skills, but contrasts in at least two ways: firstly, the form of support (vibrotactile guidance in our case vs. physically controlled movement in Grindlay's work) and secondly, and perhaps most importantly, our specific focus on multi-limb movement and multiple parallel streams of rhythmic patterns, as opposed to a single rhythmic line. In the case of Huang et al., similarities with our approach include a common focus on haptics, passive learning, and multiple body parts. Major contrasts include the use of four limbs vs. the fingers of one hand, and multiple parallel rhythms vs. monophonic melodies. Whereas Grindlay (2008) found that passive haptic training benefited learning of rhythms, Huang et al. (2010) found their participants to perform poorly on rhythm, presumably because they focused on performing the melodic note sequence correctly, slowing down when needed. In our work, the presented preliminary results indicate that the Haptic Bracelets have strong potential for learning multi-limb rhythmic skills. Like in our study, Huang et al. also used a reading comprehension task as distraction. Interestingly, the participants in Huang's study noted that perception of the tactile stimuli was (almost) subconscious, while in our study, many participants found it hard to ignore the haptics while reading. To what extent this difference relates to the position (fingers vs. wrists and ankles) or signal strength of the haptics is unclear at this stage.

6 Design Issues and Further Work

In this section, we relate the design issues emerging from participants' subjective experiences as noted earlier, to the design vision of the Haptic Bracelets, and consider the implications for further work.

Recall that the vision behind the Haptic Bracelets is of a portable music player for both active and passive learning, able to be worn all day while working on other tasks. This system should optionally play music while also optionally transmitting associated rhythms as haptic pulses delivered via lightweight, wireless, easy to don bracelets worn on wrist and ankles.

For the purposes of the research presented in this chapter, we have focused exclusively on passive learning via haptics, without accompanying music. However, future versions of the Haptic Bracelets are intended to allow stereo audio to be played back via headphones while limb-specific information is played back in exact synch via four haptic channels. This change will address many of the miscellaneous issues raised by participants, as follows.

Repetitiveness. Where music and haptic signals are synchronized, playback may not have to be so repetitive in order to support active and passive learning as when haptic stimuli are used alone. A case for this view could be made as follows. When listening to tonal, metrical music (i.e. most traditional and popular western music) there is much empirical evidence (Sloboda 1985) that beginners and experts, composers and listeners alike, all tend to be able to perceive the same wide variety of structural boundaries, using combined markers including pitch, timbre, volume and rhythm. Music is readily perceived by listeners as structured quasi-hierarchically, and this helps to make the accurate memorization and reproduction of such music far easier than the memorization or reproduction of equally long periods of arbitrary sound (Sloboda 1985). When providing haptic playback alone, much of this structuring information is not present, so that frequent repetition of short sections of material is an important aid to learning. By contrast, with accompanying music, the needed structuring and framing and context for the rhythms is far more readily provided, so that more efficient learning may be possible with less repetition. For now this argument remains speculative, and further work is required to test it empirically.

Locating the start and end points of rhythms. When a repeated haptic stimulus is used without audio, it can be hard to locate the start and end points of the rhythm. This matters because two identical repeated rhythms played with different start and end points may not be recognised as the same rhythm (Sloboda 1985). One obvious way to indicate the starting point of a haptically repeated rhythm would be to play the starting pulse more "loudly". However, this solution is not always possible, since in order to deliver clearly recognized pulses (a problem noted by participants in the study) haptic systems may play all pulses as "loudly" as possible. Another problem with such an approach is that some rhythms are most usefully conceptualized as starting on a rest. A different solution to all of these problems would be to deliver a framing pulse haptically at a different point on the body. Fortunately, however, for our purposes, this whole class of problems can be solved more easily simply by synchronizing haptic delivery with the musical context via audio. Thus, this particular design issue becomes moot.

"Holistic… less boring". More generally, likely benefits of adding synchronized musical context in the manner discussed above are well expressed by two of the participants, P5: "Might be annoying or distracting or boring to use in everyday life. Would rather listen to actual music.", and P13: "Feeling the rhythm whilst listening to the audio would be a lot better to create a more holistic understanding of the polyrhythm and the interaction needed by the limbs."

Haptic Balance. Some users found haptic stimuli harder to perceive as clearly on one limb as on another. Although the current system already allowed the experimenter to control the balance of individual tactors, this was done only once, at the beginning of each session. A straightforward refinement in future versions will be to provide a balance control for users to adjust the levels of the different vibrotacticles themselves whenever they want to.

"Use it while playing". From previous work (Holland et al. 2010), it is clear that Haptic Bracelets have diverse applications for drummers and other musicians while they are playing their instruments (for example, hierarchical click-tracks that leave the ears free, an inter-musician communication system that leaves the eyes free, rhythm section synchronization where foldback is inadequate, and training applications). Equally, the vision of learning rhythms and gaining rhythmic insights while commuting or carrying out non-music related chores is compelling. One way in which the Haptic Bracelets could have their cake and eat it in this regard would be simply to add an accelerometer to each bracelet, so that it may optionally be used to trigger chosen midi or sampled instruments. Such an 'air drum' or 'body drum' feature follows a long line of previous systems such as Zimmerman et al.'s (1986) data glove, explicitly motivated by a desire to play 'air guitar', and some Kraftwerk stage systems. See also (Andresen et al. 2010) discussed earlier, for a more recent and pleasingly simple approach to the body drum idea.

"A bit annoying… maybe a bit irritating after some time". Even if we imagine a system with all of the above design issues addressed, and even with very light, wireless comfortable and easy-to-put-on bracelets, and (crucially) appropriate off-switches, it is clear that the Haptic Bracelets may still not be for everyone.

Future empirical work. In parallel to our current development work, empirical work is planned. Key experiments will involve active and passive learning using a mobile system with synchronized music, as well as experiments with possible medical applications. Such applications could address areas as diverse as rehabilitation, conductive education, Parkinsons, Stroke, and other conditions which affect limb movement and co-ordination.

7 Conclusions

In this chapter we have presented the Haptic Bracelets and the design vision and theoretical rationale behind them; presented and analysed findings based on users' subjective evaluations; presented and analysed design implications from the evaluation; and proposed design solutions.

Results from users' subjective evaluations suggest that the passive learning of multi-limb rhythms is a promising approach that may help both in learning to play and to understand complex rhythms. All participants in our study had a positive to very positive attitude towards this use of haptic technology. They indicated several advantages of the system, including increased support for distinguishing between limbs, increased understanding of the complexity of rhythms, and 'fun to use'. An important negative finding was that the haptic buzzers got slightly irritating after a while for some participants. Many participants noted that they would like to feel the haptics in combination with hearing audio, and/or while playing the drums. Some participants commented that they did not enjoy the reading task, so in further studies, we might consider alternative distraction tasks, including tasks chosen by participants. Other interesting findings include the fact that all participants paid at least some attention to the haptics while reading. If the passive learning phase is not perceived as training, as one participant noted, this might explain why the haptics are considered to facilitate learning difficult rhythms and making the process more enjoyable. More research is necessary to determine exactly under which circumstances haptics can be used most effectively, in passive and active modes of learning.

Design issues emerging from participants' subjective experiences were noted and analysed, including repetitiveness, locating the start and end points of rhythms, holistic understanding of polyrhythms, and possible sources of irritation.

Design solutions were proposed, including provision for adjusting haptic balance, provision of air drum capabilities and an off-switch for the haptic channel. One family of design solutions that appears to address several identified problems reflects the notion of the Haptic Bracelets as resembling a portable music player, suitable for both active and passive learning, and able to be worn all day while working on other tasks. Such a system should optionally play music while also optionally transmitting associated rhythms as haptic pulses delivered via lightweight, comfortable, easy to take on and off, wireless bracelets worn on wrist and ankles. Arguments from musical psychology were detailed which suggest ways in which this arrangement might address problems including context, start and end points, and excessive repetition: it is proposed to test these arguments empirically.

Dealing with multiple parallel rhythmic streams is a central skill for drummers, but it is also vital for other musicians, for example piano, keyboard, guitar and string players. Even for the full development of rhythm skills to be exercised away from performance, such as in composition and analysis, the previous physical enaction of rhythms appears to be an essential precursor (Holland et al. 2010). Multi-limb rhythms are of particular importance to this process, because the physical enaction of many basic building blocks of rhythm, such as standard polyrhythms, is difficult without the co-ordinated use of multiple limbs. To the best of our knowledge, the use of rhythmic haptic stimuli delivered to four limbs is unique to the Haptic Bracelets and Haptic Drum Kit.

Diverse active and passive applications for drummers and other musicians were identified. These include hierarchical click-tracks that leave the ears free, inter-musician communication systems that leaves the eyes free, rhythm section synchronization systems to encourage ‘tight’ playing, and training applications.

In addition, several non-musical applications of the Haptic Bracelets were identified. These include three-dimensional navigation when ears and eyes are busy elsewhere, fitness, sports and rehabilitation, for example from strokes or injury (Huang et al, 2010). Improved rhythmic skills may be able to contribute to general well being, for example in improving mobility (Brown 2002) and alertness, and helping to prevent falls for older people (Juntunen 2004; Kressig et al. 2005).

In general terms, the present work may help, for example, to identify areas where haptics are underused in mainstream HCI. While it has always been clear that haptics can be useful where eyes and ears are focused elsewhere, the present work may help to emphasise the possible value of haptics in applications where spatial movements or temporal sequencing of movements need to be learned or communicated. It is interesting to note that specifically rhythmic applications of haptics have been very little explored in HCI. Some of the more intricate aspects of interaction with rhythm may, by their nature, be of special value to applications in Music Interaction. However, we speculate that there are applications of the rhythmic use of haptics in health, entertainment, security, safety, and other areas yet to be identified and explored.

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